Title
SUPERNOVAE: GROUND ZERO AND THE AFTERMATH

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SUPERNOVAE: GROUND ZERO AND THE AFTERMATH

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Supernovae and their remnants feed into and out of a very large fraction of the rest of astrophysics, including galaxy and star formation, nucleosynthesis, cosmic rays, and much else. The present discussion focuses on where they fit into the great scheme of things, what properties might reasonably be regarded as established and understood, some of the main problems, and what might be done next, partly by examining how we got to where we are now in SN and SNR studies.

1. What Supernovae are Good for and the Long Range Goals

Significant interactions of supernovae with the rest of the universe include (a) production of elements with $Z \geq 26$, via the r and p processes, and of iron-peak elements in Type Ia events, (b) distribution of $Z \geq 6$ elements made by hydrostatic nuclear reactions during the earlier life of the star (with some fine tuning as the shock passes through), (c) heating and stirring of the interstellar medium, (d) triggering of star formation, as seen, for instance, in rings of young stellar objects[1] and, probably, in the extinct or fossil radioactivities in the solar system[2], (e) providing the energy to accelerate cosmic rays, though the detailed connection remains mysterious (and the GCRs in turn are responsible for the production of Li, Be, and B, and some rare, odd isotopes, for many terrestrial mutations, for ionization inside giant molecular clouds, and for production of some galactic radio and gamma-ray emission), (f) measuring large distances (the realm of Dr. Leibundgut's presentation), (g) forming neutron stars and black holes, (h) cohabiting with at least some gamma ray bursters, and, most important of all, (i) keeping astronomers and astrophysicists employed.

Notice that items (c) and (d) are part of the gaseous astrophysics aspect of galaxy and cluster formation that is arguably the least-well-understood part of that problem at present. Obviously the long-range goal of such studies is to be able to integrate supernovae into detailed dynamical and chemical models of the formation and evolution of galaxies. The current stage of this program might well be described as that of the adjustable parameter, in which star formation rates, initial mass functions, the ratio of SNe Ia to core collapse SNe, and much else are fiddled until you like the answer (probably because it looks like some galaxy or other).

The data base of supernovae that can contribute to our understanding is now exponentially increasing, like nearly everything else in astronomy. For many years, the official catalogue was kept by Zwicky and his colleagues[3], and later by an Italian group[4]. Now, of course, it lives on line, but you can see where the number has got to on any day by consulting the latest IAU Circular (for instance, the announcement of SN 2002it in IAUC 8020 implies a total of 254 so far in the year, minus perhaps the retractions of a few sightings of Cepheids and such, and, yes, this still occasionally happens). The earlier record is much more spotty, with sharp rises, first, when Zwicky began the 18" Schmidt search at Palomar Mountain, and, second, when he began the 48" Schmidt survey (in connection with POSS), a sharp drop coinciding with the death of Fritz Zwicky in 1974, and a subsequent recovery particularly noticeable after SN 1987A (though I wish the IAU Supernova Working Group, refounded in 1982, could take credit). Many of the current ones are being acquired for cosmological purposes, and not all get adequate follow-up in the form of spectra and light curves. Indeed not all are bright enough for this to be possible. Any statement about which properties pertain to which SN types and subtypes is, of course, subject to reservations based on the inventory being finite and, in some cases, actually fairly small.

2. Supernovae and Supernova Remnants: Definitions, Types, and Connections

A modern definition of a supernova would not sound particularly foreign to Baade and Zwicky[5], whose version goes back to 1933. First, optical brightening by at least 10^{mag} (this is typically a limit, very few progenitors have been recorded in advance) in months or less, with duration more than a month or two, and subsequent fading within a year or two, and location not precisely at the center of an otherwise active galaxy (this bit would surprise B&Z). Some, but not all, SNe also display outbursts in radio and X-rays.

The observed types are defined by their spectra, and so none of the pre-telescopic events can be absolutely assigned to a type (though, of course, if the remnant is full of hydrogen, it is a pretty safe bet that the event would have been too). The Type II events display hydrogen features and the Type I's do not. Subtypes of Type II's, called IIL and IIP have respectively, linear and plateaued declining light curves (in logarithmic units), and the IIn's show evidence of dense material around them. The Type Ia, Ib, and Ic are distinguished by the evolution of particular spectral features due to helium and silicon.

The total range of SN light curves is in fact very broad, and some events, including SN 1054 and SN 1885 (S And) are not assignable to any known type from the available light curves. The peculiarities of SN 1987A were largely attributed to the progenitor being a blue rather than red supergiant (this is an observation!) and its exponential decline was not particularly anomalous, though of course it has been followed for many more years than any previous event.

Supernovae were, as it were, born with their remnants in place, because early 20th century novae (like nova 1901 Persei) had shown conspicuous shells of rapidly moving ejecta, and indeed the connection between the Crab Nebula and the 1054 event recorded by the Chinese (etc.) was suggested by Knut Lundmark[7] before the nova/supernova distinction was generally recognized (though Lundmark himself was among the first to suspect that there might be two classes, along with Heber Doust Curtis[8]), and see Trimble[9] for more on the early recognition of SNRs and their association with particular events. Convenient criteria for recognizing an SNR today include non-thermal radio emission, optical line ratios indicating that a wide range of ionization states co-exist, and X-rays. There are occasional disagreements and changes of mind about whether particular fuzzy things belong to the class (for instance the nebula around SS 433),

The customary types of SNRs are (a) shells, which are brightest at their edges in radio, X-rays, and optical (if not obscured), (b) plerions, meaning filled centers, with fairly uniform surface brightness rising toward the center; some, at least, are pulsar fed, and (c) composite, meaning that both the edge and some center bits are bright. Some are associated with neutron stars or pulsars; in other cases the bright bits may just be compressed interstellar or ejected material[10].

Some supernovae have pulsars or other neutron stars in them (presentation by Dr. Manchester). For many years the list was the Crab Nebula, er, Vela, and, oh, um, 0540 in the LMC. It is now considerably longer.

Connections between specific supernovae and remnants are of two kinds, "historical" and "recoveries," THE authority on the historical (galactic) events is now unambiguously the new book by Stephenson and Green[11]. They are very austere in their conclusions, endorsing only SN 1054, 1572, 1604, 1181, and 1006 and denying their blessing both to a Flamsteed observation of the event giving rise to Cas A and to European observations of the 1054 event. Thus the last two lines of Table 1 appear without their endorsement! Indeed they do not regard any events in the Chinese (etc.) records from before 1006 as being clearly identifiable as supernovae. Other (unblessed) suggestions in recent years have included SS 433 = SN 837 and SN 1523 = Kes 75 (which harbors a 0.324 sec pulsar with a slowing-down age near 700 years).

Table 1. The historical supernovae. The last two are not endorsed by Stephenson and Green[11].

EVENT YEAR	REMNANT	NEUTRON STAR/PULSAR
1054	Crab Nebula	NP0532, P = 0.33 sec
1572	3C 10 (Tycho)	No
1604	G 4.5 + 68 (Kepler)	No
1006	PKS 1459-41	No
1181	3C 58	P = 0.0658 sec (X-ray)
1680	Cas A (Flamsteed's star???)	Compact, unpulsed X-ray core
386	G 11.2-03	P = 0.54 sec psr

After a supernova has officially faded below detection, it may become visible again either because technology has improved (e.g. the Fe absorption feature associated with S And!) or because ejecta plowing into dense material shed by the progenitor heat up and shine again. The expert on optical recoveries is Rob Fesen, starting with SN 1970G in 1993[12]. And the expert on radio recoveries is Kurt Weiler[13] , holding the current record for "oldest young supernova" or some such, with 1923A. All of these recoveries are events associated with core collapses in massive stars (Types Ib, Ic, or II, to anticipate the next section), so that one expects dense surroundings.

Some Preliminary Numbers and Theoretical Types

Observations tell us that the integrated electromagnetic radiation of supernovae is typically at least 10^{49} ergs and the kinetic energy of the ejecta about 10^{51} ergs (one to 10's of solar masses moving at a few to a few tens of thousands of km/sec). The required cosmic ray input to keep up the galactic supply is 10^{50-51} ergs per event (this is an observation, but the conclusion that the energy actually comes from SNe is not!), and the input to general heating and turbulence of the ISM comparable. The binding energy of a neutron star is about 10^{53} ergs, the kinetic energy of a 10 msec pulsar is 10^{50-51} ergs (depending a bit on the equation of state assumed for dense nuclear matter), but the magnetic field energy stored in a 10^{13} G pulsar is only 10^{44} ergs.

The standard interpretation is that Type Ia events are the result of a nuclear explosion (detonation and/or deflagration, of which more later) of a Chandrasekhar mass of degenerate carbon plus oxygen, with Ni^{56} as the dominant product. It takes about 0.6 $M_\odot$ of Ni^{56} to account for 10^{51} ergs in the explosion and, because the light curve is then powered by the decay of this to Fe^{56}, one expects event luminosity, spectrum, and light curve all to be correlated.

All other types are associated with collapses of the cores of massive stars which have built up a Chandrasekhar mass of iron-peak elements. Further distinctions depend on the amount of residual hydrogen-rich envelop, with the Ib's and Ic's having been completely stripped by winds and/or binary companions.

3. Brief Histories of Supernova Studies and of the Crab Nebula

The items indicated here are a small, and very arbitrary, subset of all the things that might be said. The two lists are approximately, though not perfectly, chronological.

1572. Tycho sees "his" supernova and sets a limit to its geocentric parallax smaller than that of the moon, establishing that the heavens are not "immutable". Galileo's discussion of reconciling Tycho's and other discordant parallax estimates leads to his inventing what would now be called a statistical method of least errors[14],

1885. S And peaks at an apparent magnitude close to that of many previous novae in the Milky Way, leading many astronomers to increased confidence that M31 and the other spiral nebulae were inside the MW. This goes in the historical category called "oops."

1920-21, Two classes of novae of very different intrinsic brightness are "not impossible" according to Curtis[8] and Lundmark[15].

1932. Name "supernova" coined by Lundmark[16]. Credit for the name has generally been ascribed to Baade and Zwicky a couple of years later, even by the Oxford English Dictionary. But they have promised a correction.

1933-34. Modern definition of the class of supernovae, including S And and the 1054 event as examples. Energy attributed to the collapse of a normal star to a neutron star, and suggestion that some of this energy goes into accelerating cosmic rays, Walter Baade and Fritz Zwicky[5].

1941. Two basic spectral types according to Minkowski[17] . By chance, the first six events discovered by Zwicky had all been of Type I, but Humason[18] had earlier suggested that the spectrum of SN 1936A was dominated by hydrogen features.

1941-73. SN I spectral features = emission and/or absorption by common elements, excluding hydrogen and helium. First quantitative attempt to match spectra by Whipple and Payne-Gaposchkin in 1941[19]. Later ones from Mustel[21] , Gordon[24] , Pskovskii[20], and others, led to general convergence in about 1973 that the spectra were essentially very broad P Cygni lines of O, Mg, Si, Ca, Fe, and such[22,23].

1946. Nuclear mechanism for SN explosions put forward by Gurevich and Lebedinsky[25] (in a paper that is also one of the very first suggestions that novae are the result of nuclear explosions on a white dwarf surface). Sold persuasively to the community in 1960 by Hoyle and Fowler[26].

1940. Exponential tails of SN light curves represent radioactive decay, according to Zwicky[27], in what was probably the first supernova review article. Borst[28] in 1950 suggested that Be^7 would have about the right half life. B^2FH[29] proposed Cf^{254}, Pankey[30] put forward Ni^{56} , and the endorsement of this by Colgate[31] more or less settled the issue. Lyle Borst is still to be found among the members of the American Physical Society, though Pankey is not. You are presumed to know all about the other people in this saga.

The Crab Nebula is both the first and the quintessential SNR, and here to a certain extent does duty for the whole class.

5465 BCE. Photons leave CM Tau. This date is, of course, largely arbitrary. The distance to the nebula is about 2 kpc but is not known to two significant figures!

1054 CE. Photons reach China, Japan, Korea, and Constantinople, but apparently not Europe[11].

1731. John Bevis sketches a fuzzy patch for his *Uranographie Britannica.*

1785. The patch is truly diffuse and not resolvable into stars, says Lassell[32]. The stars in his drawing are sufficiently close to those shown in modern photographs that the author wonders whether careful examination of 18th and l9th century drawings of what we now know to be extragalactic nebulae might not yield a small sample of 150-300 year old SNe for potential recovery, in an otherwise unrepresented age range.

1892, First photograph (Isaac Roberts), The first published photograph seems to have been that taken from Poulkova Observatory by Kostinsky in 1896 and reproduced by Deutsch and Lavdovsky[33]. Kostinsky himself published his last paper just 40 years later[34] in the same issue of POC that contained the last word from Gerasimovich. It was not a good year in which to be a Russian astronomer who had had extensive contact with colleagues in other countries.

1921. The nebula is truly variable, said Lampland[35], only about the third of which this could be said on the basis of photographic evidence. Somehow nearly all nebulae were variable in 19th century and earlier drawings. He was looking at the non-thermal, wisp component that was later the purview of J.D. Scargle and, most recently, of Jeff Hester and the HST.

1916. The spectral emission lines extend to high velocity, according to Slipher[36].

1921. The nebula is expanding, found Duncan[37], now looking at the thermal, emission line component, and has been doing so for about 900 years.

1942 The south preceding star is the neutron star, Baade and Minkowski[38]. It is, by the way.

1948. Crab is the counterpart of the radio source Taurus A, Bolton & Stanley[39] and the radio emission is polarized[40], though this was a later discovery.

1954. The optical emission is polarized[41,42]. For no very good reason, I attempted to track down the later career of V.A. Dombrovsky. He seems to have spent a large portion of it in search for optical polarization in other nebulae, both planetaries and HII regions, without much success. The optical emission should have been polarized because it is synchrotron emission. This was said in advance of the observation by, at least, I.S. Shklovskii and V.L. Ginzburg. Each has told his own story[43,44], and I shall not attempt adjudication here. One conference participant (a Ginzburg student) felt that more credit should also be given to I.M. Gordon ([45] for instance) an earlier Ginzburg student. It is anyhow safe to say that, although synchrotron emission had laboratory and Western European roots, the application to the Crab Nebula (and probably also to solar radio bursts and galactic diffuse emission), and the confirmation were Soviet/Russian contributions.[46,47]

1964. Existence of a compact radio core in map by Hewish and Okoye[48] . I was beginning my thesis research on the Crab at this time and, with either a little less guidance from my advisor, or a little more good sense would surely have suggested the core as being somehow relevant to the problem of the lifetime of the optical and X-ray synchrotron electrons being much less than 900 years.

1963. Discovery of X-ray counterpart[49]. This was initially assumed to be compact and led to large numbers of investigations of cooling of neutron stars, many of which have modern descendents, though the source was shown the next year, during the next lunar occultation, to be extended[50], and thermal X-ray emission from neutron stars remains a bit elusive even now (Presentation by Dr. Pavlov). The X-rays were eventually shown to be polarized[51], with the only X-ray polarimeter flown to date.

1967, Gamma ray emission[52], later found to be pulsed in re-examination of the data returned from this balloon flight.

1968, NP0532[53], its optical counterpart[54], time derivative[55], glitches[56] (though Vela glitched earlier the same year), and second time derivative[57].

Despite, or perhaps because of, all this, there remain several aspects of the Crab SNR that I, at least, am puzzled by. First is the mechanism by which energy starting as 33 Hz electromagnetic radiation at the pulsar ends up as electrons energetic enough to radiate X-ray synchrotron. The pioneering study by Rees and Gunn[58] predicted more circular polarization near the center than is seen (because the energy was carried for a considerable distance as very low frequency EM radiation). A modified version[59], which applies to the Crab and a number of other plerions, has about 99.9% of the energy flux in particles (see also [60]). In contrast, the two fluxes are about equal when leaving the Vela pulsar[61].

Second, is the motion of the non-thermal wisps (now seen in both optical and X-ray emission) actually periodic? And, if so, why? Hester et al.[62] provide a link to a site that displays both optical (HST) and X-ray (Chandra) images of the motions in (almost) motion picture format. These may not answer the questions for you but will perhaps help you decide whether you want to ask them.

Third is the nature of the van den Bergh jet[63]. This does not actually look much like a jet, but more as if someone had accidentally dragged his thumb outward from the northern rim of the nebula on a wet photographic plate. This is not the right answer, however, since the feature has been seen many times, and appears in any deep exposure, including some of my own plates, taken before 1970. It is about 100" (1 pc) long and a third that width and points back only approximately to the center of the nebula or the position of the pulsar. At the time, many models were put forward, ranging from the trail of an ejected former companion to the progenitor to a leak in the main nebula, but we have not spotted any promising new thoughts or confirmations of old ones in the last decade or so, since the "star trail" of Cox et al.[64] It is also detectable in radio images, and if there were another one on the other side, we could just say "bipolar jet" and go home.

Fourth, where is the rest of it? The ionized, thermal gas amounts to 1-2 $M_\odot$ [65], and the pulsar as much again, The synchrotron gas is exceedingly tenuous, and, while there is some dust and hot H_2, the cold components are also very small. Yet it takes an 8-10 $M_\odot$ star to make a core-collapse supernova, even one like SN 1054 that is enriched only in helium[65,66]. The rest ought, of course, to be outside (as it is for SN 1987A) in the form of an extended, cool halo of superwind or AGB ejecta, into which the visible nebula is now expanding. And, indeed, there have been sporadic reports of a halo in some form, for instance Hα emission[67]. But that emission is probably from a background source[68] (with the Crab expanding into some sort of bubble), and nor is there any evidence for a radio halo[69]. Something like 10 other SNRs of various ages are similarly bereft of evidence for rim brightening at any wavelength[60]. The present author once reported[70] evidence for heating at the outer edge, in the form of an increase outward in the ratios of lines of high excitation potential to those of low excitation potential (note that lines of high ionization potential are concentrated toward the center and this is attributed to ionization by the center brightened UV synchrotron continuum), but no one believed it at the time, so why should you now!

Finally, did the pulsar really make a significant contribution to the light seen back in 1054? Sollerman et al.[71] have taken a look at the declining light curve and concluded that, given how long the guest star remained bright, there must have been energy input from (a) collision with surrounding material (which we have just noted that there is no evidence for) or (b) a good deal of Ni^{56} (which would now be extra Fe^{56} for which, again there is no evidence), which leaves (c) a very bright pulsar. The evidence against this hypothesis, which would require the pulsar period initially to have been quite short, is rather indirect[72,73], and the idea would seem to be the first unqualified "yes" answer to the 30-plus year old question of Ostriker and Gunn[74], "Do pulsars make supernovae?"

4. The Things We Think We Know

Foremost among these is the correlation between spectrally-defined event type and energy source. SNe Ia arise from explosions of about a Chandrasekhar mass of carbon and oxygen up to iron peak elements, and no compact remnant is expected or found, e.g. Reinecke et al.[75] and any of a half dozen or more other papers every year for the past couple of decades. Both brightness and kinetic energy of the disrupted material scale with the amount of iron-peak material made. Type Ib and Ic supernovae are also largely free of hydrogen in their spectra, at least at and beyond peak, according to [76] and [77], and, again, many others. The hydrogen shell must have been removed either by a vigorous wind or by binary mass transfer. Finally, the SNe II's, with hydrogenic spectral features, arise from core collapse of massive, incompletely stripped stars. They are about four times as common as the stripped core collapses[78], and core collapse events are, in general, a good deal commoner than nuclear explosions, except in galaxies without ongoing star formation, where the SN Ia are the only sort that occur[79].

SNII subtypes depend both on the amount of Ni^{56} ejected and on the density of the immediate surroundings[80]. The remnant core can settle down as a neutron star or go on immediately to a black hole[81]. As noted earlier, all radio, X-ray, and early recovery SNe are core-collapse types and involve ejecta hitting stuff, but cases like the progenitor of SN 1987A, in which a phase of vigorous mass loss is followed by the star looping back to the blue are exceedingly rare[82]. Core collapse events eject a range of heavy elements, especially the alpha-nuclei (O^{16}, Ne^{20}, Mg^{24}, etc.) and r process products[83,84]. Finally, core collapse explosions can be sufficiently asymmetric to unbind binary pairs (which the symmetric lost of less than half the total system mass can never do) and to give neutron stars "kick velocities," but not always.[85,86]

Nuclear explosions eject a mix of unburned C and O, iron peak, and some intermediate products[75]. They can happen among very old star populations, but are nevertheless commoner (for instance in SNU's, rate per century per 10^{10} solar luminosities) in star-forming galaxies, The statistics suggest a delay time between star formation and SNe Ia near 10^8 years[87,79,88].

In accordance with the claim that these matters are things we know, the references cited are drawn indifferently from the observational and theoretical literature!

5. The Things We Would Like to Know more About

The previous section consists of topics that speakers at current conferences on supernovae and such are likely to have worked on. This section contains topics that you might want to put your graduate students to work on.

5.1. *Rates, Types, and Parent Populations*

These are the issues that feed most directly into "gastrophysics" of galaxy formation and evolution. In units of SNe per century per 10^{10} $L_\odot$, Zwicky's number was 1.29 (corrected to the modern distance scale). Modern rates are somewhat smaller in early type galaxies, larger in late type ones, but the values always have error bars that are a factor of two or more, and this gets worse when events are divided up by type and subtype. Even more sparse are data on how SN numbers and the distribution of types has changed with time[89,90], one of which gives 0.02-0.88 SNU as the range of possibility for type Ia events near $z = 0.4$. It is perhaps not more than idle curiousity to wonder whether the 6 events in M101 in historic times exceeds the tail of some Gaussian distribution.

Another issue of global import is the chemical composition of ejecta from events of various types, as a function of progenitor mass and whatever else might be important. Actual data are very sparse - among the Type II's only six have both an ejected-Fe and a progenitor mass estimate[83], and only those for SN 1987A (which was probably not a typical event) are good to much better than a factor two. Thus most of what we say is known about yields comes from computations like those of S.E. Woosley and his colleagues[93]. I know no a priori reason to distrust these, but, as people in remote sensing say, one would like some ground truth. The situation for nuclear explosion SNe is quite similar. There are measured values for only a few events and elements (e.g. 0.22 $M_\odot$ of Fe in the remnant of S And[91], the small number being anyhow consistent with the event having been very fast and rather faint), plus computed numbers for many[92,75], and the curious observation that Ia ejecta must be more homogeneous (in latitude and longitude) than you would expect, since the time development of the spectra is rather similar for nearly all.

Wanting to understand the physics of the events themselves is the main reason for wanting additional information on the correlations between event types, remnant types, and whether the core is left as a neutron star or black hole. In particular, one would like to know just what is lurking at the center of Cas A and of 1987A and the nature of the associations of the anomalous X-ray pulsars and soft gamma repeaters with recognizable SNRs[95,96].

Identification of the progenitors of Type Ia events remains the problem on which least progress has been made in the past decade or two, I think. The best fit to the light curves continues to come from pairs of white dwarfs with total mass in excess of the Chandrasekhar limit and orbit periods short enough that they will merge in a Hubble time[97]. Cases have also been made for recurrent novae[98], supersoft X-ray binaries[99], and symbiotic stars[100], in all cases because the white dwarf mass is quite close to the Chandrasekhar maximum and some burned material is staying put on their surfaces. The problem with all these is that the companion is likely to shed stray hydrogen into the neighborhood of the event which, by definition, we do not see. The "best buy," candidate, massive binary WDs, currently has precisely zero examples in the archival literature, but a participant mentioned an on-going radial velocity survey of about 1000 white dwarfs that has recently uncovered one potential member of the otherwise empty class. This may actually be enough. Although WDs are born at a rate of about one per year and the SNIa rate is close to one per century, (suggesting 1% of the WDs should be candidate progenitors), systems may pass through the recognizable set of properties a good deal faster than the 10^{10} years it takes a white dwarf to fade to oblivion.

While we're at it, let's look at Ia mechanisms. The published inventory includes detonation and deflagration (super- and sub-sonic propagation of the burning front), and hybrids like off-center and delayed detonation. One worries about this, perhaps, mostly because the different mechanisms imply different nucleosynthetic outcomes[101], and the solution has to be observational, we think, a calibration of ejected composition vs. light curve types. In contrast, the most worrisome item about the uncertainty in progenitors is that there may actually be more than one (core carbon detonation in a single star was also historically part of the inventory), and the mix could vary with redshift, affecting the use of even calibrated SN Ia's as distance indicators.

For Type II and other core collapse events, the long standing problem has been one of energetics. Yes, there is 10^{53} ergs available, and you need impart only about 1% of this to the outer layers of the star to get a respectable supernova, but the hopeful shock that sets off when the collapsing core reaches nuclear density and bounces has always had a tendency to get stuck and waste its energy on photodisintegrating heavy nuclei as they fall back through and so forth. The stars, of course, have solved this problem, and astrophysicists have announced solutions a number of times over the years. Neutral currents, neutrino-driven convection, and so forth, and, particularly, larger asymmetries than you would have expected before doing the two- and then three-dimensional calculations have been part of the on-going saga. A difficulty, of course, is that, if you make space in your computer for a 3-d grid, you will necessarily have to treat the rest of the physics with some approximation scheme. Thus there is no absolute guarantee that the epoque 2002 solution is[102] the final one either.

The progenitors of core-collapse supernovae have been known to be massive stars for decades, and we see no reason to doubt the basic scheme. Only two or three have been imaged before the catastrophe: 1987A, of course, 1993J (the prototypical SN Ib) [103], and 1961V, which is probably some sort of luminous blue variable rather than a supernova, because it has never properly gone away. A somewhat larger number do not appear down to some limiting magnitude in images of their fields taken for other purposes (unfortunately, they do not come with error boxes labeled "watch this space; supernova due in 11 years"). The limits are in the range 10-12 $M_\odot$ though 1986J ejected at least 12 $M_\odot$ in unprocessed hydrogen alone[104,80,106]. The "action item" here clearly has to be to measure masses and compositions of ejecta from more events. The ongoing difficulty is that, when they are bright, most of the light is typically coming from the relatively unprocessed envelope, and by the time the material is fully revealed, it is too cold and faint to see. SN 1987A is offering us a second chance, because the X-rays will, in the future, come from shocks that involve deeper and more processed layers of the parent star.

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husband, Joseph Weber, who REALLY knew what "controversial" means.

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